Improvements to the Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN)

William R. Doggett[1], John T. Dorsey[2], Thomas C. Jones[3], Kenneth N. Lodding[4], George G. Ganoe[5]
NASA, Langley Research Center, Hampton, VA 23681, USA

David Mercer[6]
Stinger Ghaffarian Technologies, Hampton, VA 23681, USA

and

Bruce D. King[7]
Northrop Grumman, Hampton, VA 23681, USA

Devices for manipulating and precisely placing payloads are critical for efficient space operations including berthing of spacecraft, in-space assembly, construction and repair. Key to the success of many NASA space activities has been the availability of long-reach crane-like devices such as the Shuttle Remote Manipulation System (SRMS) and the Space Station Remote Manipulation System (SSRMS). These devices have been used for many operations including berthing visiting spacecraft to the International Space Station, deployment of spacecraft, space station assembly, astronaut positioning, payload transfer, and spacecraft inspection prior to atmospheric re-entry. Retiring the Space Transportation System has led to the removal of the SRMS from consideration for in-space missions, thus creating a capability gap. Recognizing this gap, work was initiated at NASA on a new architecture for long-reach space manipulators. Most current devices are constructed by joining revolute joints with carbon composite tubes, with the joints accounting for the majority of the device mass. For example in the case of the SRMS, the entire device mass is 410 kg (904 lbm); the joint structure, motors, gear train, cabling, etc., accounts for the majority of the system mass because the carbon composite tubes mass is 46 kg (101 lbm). An alternate space manipulator concept, the Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN) was created to address deficiencies in the current state-of-the-art in long-reach manipulators. The antagonistic tendon actuated joint architecture allows the motors actuating the joint to be removed from the joint axis, which simplifies the joint design while simultaneously providing mechanical advantage for the motors. The improved mechanical advantage, in turn, reduces the size and power requirements for the motor and gear train. This paper will describe recent architectural improvements to the TALISMAN design that: 1) improve the operational robustness of the system by enabling maneuvers not originally possible by varying the

---

[1] Research Engineer, Structural Mechanics and Concepts Branch, MS 190, Associate Fellow.
[2] Senior Research Engineer, Structural Mechanics and Concepts Branch, MS 190, Senior Member.
[3] Research Engineer, Structural Mechanics and Concepts Branch, MS 190, Member.
[4] Computer Engineer, Flight Software Systems Branch, MS 472
[5] Computer Engineer, Electromagnetics and Sensors Branch, MS 473.
[6] Computer Engineer, Structural Mechanics and Concepts Branch, MS 190.
[7] Senior Designer, Aeronautics Systems Engineering Branch, MS 238.

TALISMAN geometry; 2) enable efficient active antagonistic control of a joint while sharing cable between antagonistic tension networks; and 3) uses a unique arrangement of differential capstans to reduce motor torque requirements by an order of magnitude. The paper will also summarize recent efforts to enable autonomous deployment of a TALISMAN including the deployment concept of operations and associated hardware system design. The deployment forces are provided by the same motor systems that are used for articulation, thus reducing the mass associated with the deployment system. The deployment approach is being tested on a TALISMAN prototype which is designed to provide the same operational performance as a shuttle-class manipulator. The prototype has been fabricated and is operational in a new facility at NASA Langley Research Center that has a large area (15.2 m by 21.3 m [50 ft by 70 ft]) air-bearing floor.

Nomenclature and Acronyms

C_L	=	length of the lower cable
C_U	=	length of the upper cable
D_{CM}	=	distance on cable management side
D_{WL}	=	distance on working load side
L	=	link length
R	=	radius
R_L	=	large capstan radius
R_S	=	small capstan radius
S	=	spreader length
SOA	=	state-of-the-art
SRMS	=	Shuttle Remote Manipulation System
SSRMS	=	Space Station Remote Manipulation System
TALISMAN	=	Tension Actuated In Space MANipulator
T_H	=	torque at the handle
W	=	weight

I. Introduction

The Tension Actuated In Space MANipulator (TALISMAN) created a new structural architecture for long-reach manipulators. This long reach arm uses a series of tension members (often cables) for both structural stiffening as well as joint actuation.[1,2] This unique arrangement of tension elements simultaneously provides improved structural performance and improved mechanical advantage for the motors. Compared to state-of-the-art (SOA) long-reach in-space manipulators, such as the Shuttle Remote Manipulator System (SRMS) and the Space Station Remote Manipulator System (SSRMS), a TALISMAN-based manipulator with equivalent stiffness in the plane of the cables provides an order of magnitude reduction in mass and nearly an order-of-magnitude reduction in packaging volume.[3,4] In Fig. 1, the top image depicts a TALISMAN in the deployed state and the bottom image depicts the manipulator in the packaged state. The links and spreaders form the compression structure while the tension segments form the tension and actuation network. Arrows in the figure point to the same link, spreader and motor in both the deployed state and packaged state to aid in visually tracking the components. Also, links are different colors so that they may be identified in the packaged state. The motors that actuate the joints are remote from the axis of rotation of the joint which improves mechanical advantage and improves the ability to package the manipulator compactly. The architecture is scalable, with increases in length resulting in a nearly linear increase in mass. Also, the ratio of spreader height to link length can vary depending on mission requirements.

The motivation for the TALISMAN architecture resulted from observing that in the current SOA (represented by the SRMS) the joints account for the majority of the device mass. For the SRMS, the overall device mass is 410 kg (904 lbm) with the carbon composite tubes mass is 46 kg (101 lbm) or 11.2% of the system.[5,6] The majority of the remaining mass (88.8%) is attributed to the joint structure, motors, gear train cabling, i.e., the actuation system. Observing that reducing the torque requirements on the motors is necessary to reduce actuation mass fraction led to the TALISMAN architecture; where the motors are located remote from the joint axis and tension elements are used to provide

significant mechanical advantage about the joint axis. The tension elements are also designed to provide link stiffening. This increased structural stiffening is analogous to that realized in bridge design as shown in Fig. 2. For moderate spans, beams are used to support a roadway (Fig. 2a), but for larger spans (Fig. 2b) tension supported spans are used because of their improved structural efficiency. Similarly, SOA in-space robotic manipulators, such as SRMS and SSRMS, are constructed by joining revolute joints with efficient carbon composite tubes (Fig. 2c), however the TALISMAN uses a tension stiffened architecture (Fig. 2d), resulting in reduced mass and stowed volume for the manipulator. In addition, placing the motors remotely from the joint axis overcomes significant shortcomings of the current SOA, including the need to generate large torques over small distances, which results in large and massive gear train/motor combinations. The motor location remote from the joint axis in the TALISMAN architecture also alleviates crowding near the joint axis where joint articulations, gearing and motors, along with the associated electronics and cable harnesses are all vying for space in the SOA systems.[7]

In this paper, three significant improvements to the TALISMAN architecture are disclosed. The first is the ability to actively change the geometry of the TALISMAN components during operation. This important capability allows the device geometry to vary to avoid obstacles, change mechanical stiffness or change actuator authority, or to optimize performance for a specific maneuver. The second significant improvement disclosed here is an arrangement of capstans that enable each tension segment to be actively controlled while using one or two tension elements per joint. The tension element or cable circulates from one side of the link to the other side during operation as the joint articulates and this can be accomplished with multiple capstans on a single cable without having springs in the load path. The third significant improvement is a unique cable arrangement that uses a pair of differential capstans to reduce the torque required by the motor by over an order of magnitude. This improvement directly reduces the mass and power requirements of the motor, brake and gear train.

A recent focus has been to enable autonomous deployment of a TALISMAN. The resulting hardware design not only enables efficient deployment, it provides the ability to move the spreader from one side to another during operation, i.e., reconfigure dynamically for specific maneuvers. The hardware system has been fabricated and is undergoing testing using a TALISMAN prototype designed to provide the same operational performance as a shuttle-class manipulator. The device is being tested in a new facility at NASA Langley Research Center that has a large area, 15.2 m by 21.3 m (50 ft by 70 ft), air-bearing floor.

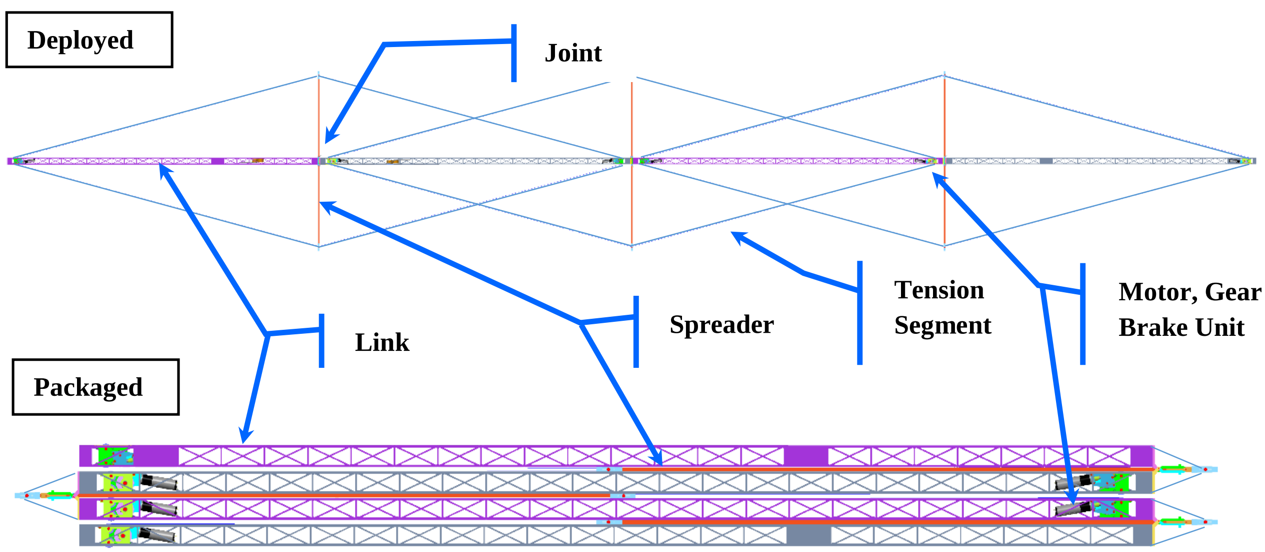
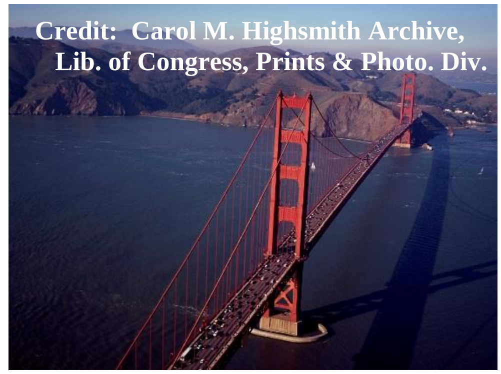


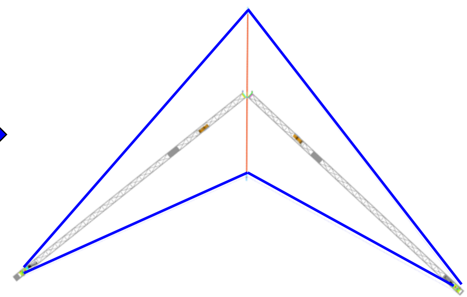
Figure 1. TALISMAN in the packaged and deployed configurations.

a. Beam-supported bridge span



b. Tension-supported bridge span

c. SSRMS, beams connect joints



d. TALISMAN, Tension structure supports joints.

Figure 2. Comparison of beam and tension supported structures.

II. Variable Geometry for Obstacle Avoidance and Performance Optimization

The first improvement described is the ability to reconfigure the geometry of TALISMAN components during operation which will be described using a simplified TALISMAN joint system depicted in Fig. 3, where the motors

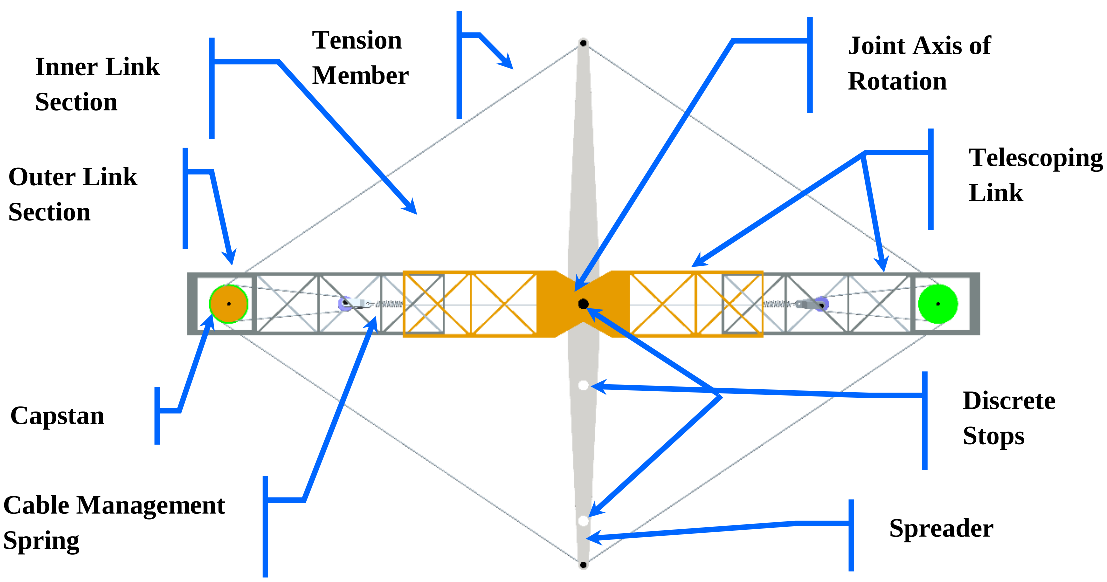
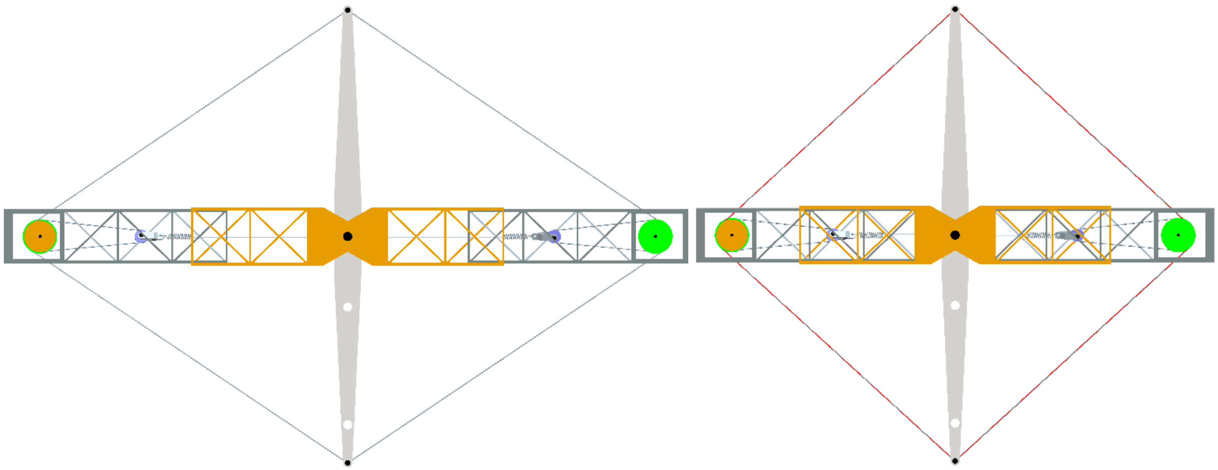


Figure 3. TALISMAN based joint illustrating two methods to reconfigure geometry.

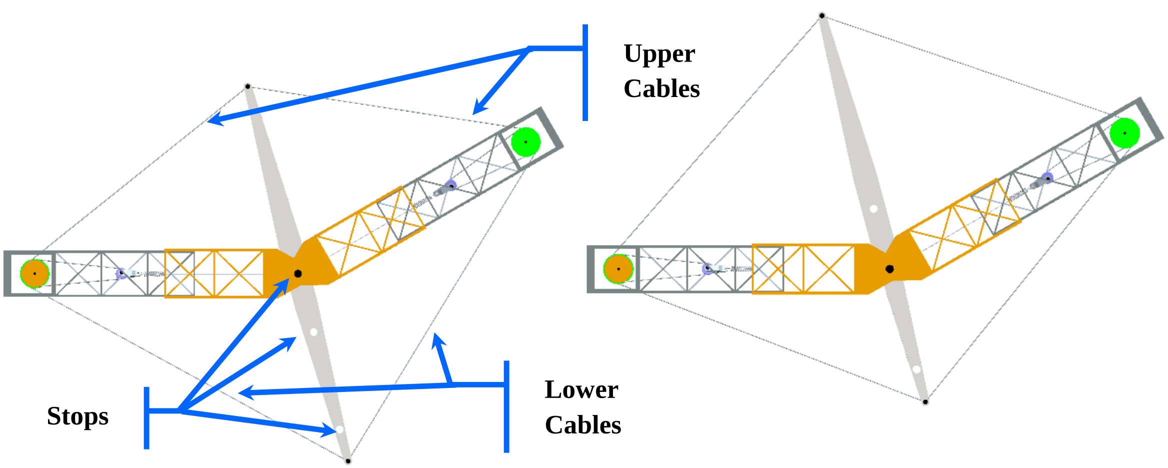


a. Links extended **b. Links retracted**

Figure 4. TALISMAN link telescoping.

have been omitted to enable the cable routing to be visible. The capability to change geometry enables both compact packaging for launch and improved operational versatility and performance, including the ability to reconfigure to 1) avoid obstacles during operation, 2) increase stiffness, and 3) improve actuator control authority. The key features of a TALISMAN joint are 1) the compression members (i.e., the links and spreaders), 2) the tension members, 3) the joint axis of rotation, 4) the capstans, and 5) the cable management spring as shown in Fig. 3. Here, the tension element will be referred to as a cable for simplicity, but the element may be a cable, rope, tape, or combination of these and rigid elements. There are many possible methods to reconfigure the geometry of TALISMAN components, two methods will be described here. The first method to reconfigure the geometry of the links is to change the link length; for example the overall link length can be shortened. In Fig. 4, one possible length changing method, telescoping sections, is illustrated, where the outboard grey sections are telescoped into the inboard orange sections. The links are shown in Fig. 4a fully extended while the links are shown in Fig. 4b retracted. Although both links are shown retracted in Fig. 4b, it is possible to only telescope one link depending on requirements of the task.

It is also possible to change the geometry of the spreader. In the simplified joint shown in Fig. 3, a monolithic spreader is used, i.e., a single fixed-length component forms the spreader for the joint. The spreader could be composed of



a. Spreader centered **b. Spreader offset**

Figure 5. TALISMAN spreader reconfiguration.

multiple components, each of which may be deployable, enabling one side of the tension network (above the links for example) to change independently of the other side of the tension network (below the links). For simplicity, in the current description, three discrete stops in a fixed-length spreader are identified. The black pin at the center of the joint can release and reengage the spreader, at a different stop location, enabling the spreader to change location relative to the joint axis of rotation, as shown in Fig. 5b. In Fig. 5a, the spreader is centered relative to the axis of rotation of the joint, while in Fig. 5b the spreader has been repositioned upward.

An important feature of the TALISMAN architecture is that the spreader reconfiguration shown in Figs. 4 and 5 can be accomplished using the link articulation motors. By varying the tension in the cables or the angle of action of the tension cables, the spreader can be repositioned from one side to the other by simply releasing and reengaging a locking pin. Relaxing the tension in the upper cables and increasing the tension in the lower cables for the configuration shown in Fig. 5a, then releasing the pin will cause the spreader to move to the position shown in Fig. 5b. Although this is a dynamic event; as the spreader is moving, the joint is articulating; with proper control, the maneuver is straight forward. Likewise, the telescoping action shown in Fig. 4 can be accomplished using the link articulation motors. Retracting the outer link section is straight forward, accomplished by increasing the tension in the appropriate cables. Extending the outer links is accomplished by reacting against a temporary anchorage, as shown in Fig. 6, or by swinging the link rapidly enough to generate sufficient outward dynamically induced force to allow the outer link to be released and then re-engaged in the extended position. One of many possible maneuvers to extend the last outboard link (the link between the distal joint and wrist) using a temporary anchor location is depicted in Fig. 6. In this example, the wrist connects to an anchor location and then the proximal joint rotates clockwise while the distal joint rotates counter clockwise as shown, which extends the last link. As has been shown, it is possible to reposition the spreader, as well as extend and retract links using only the motors required for articulating the

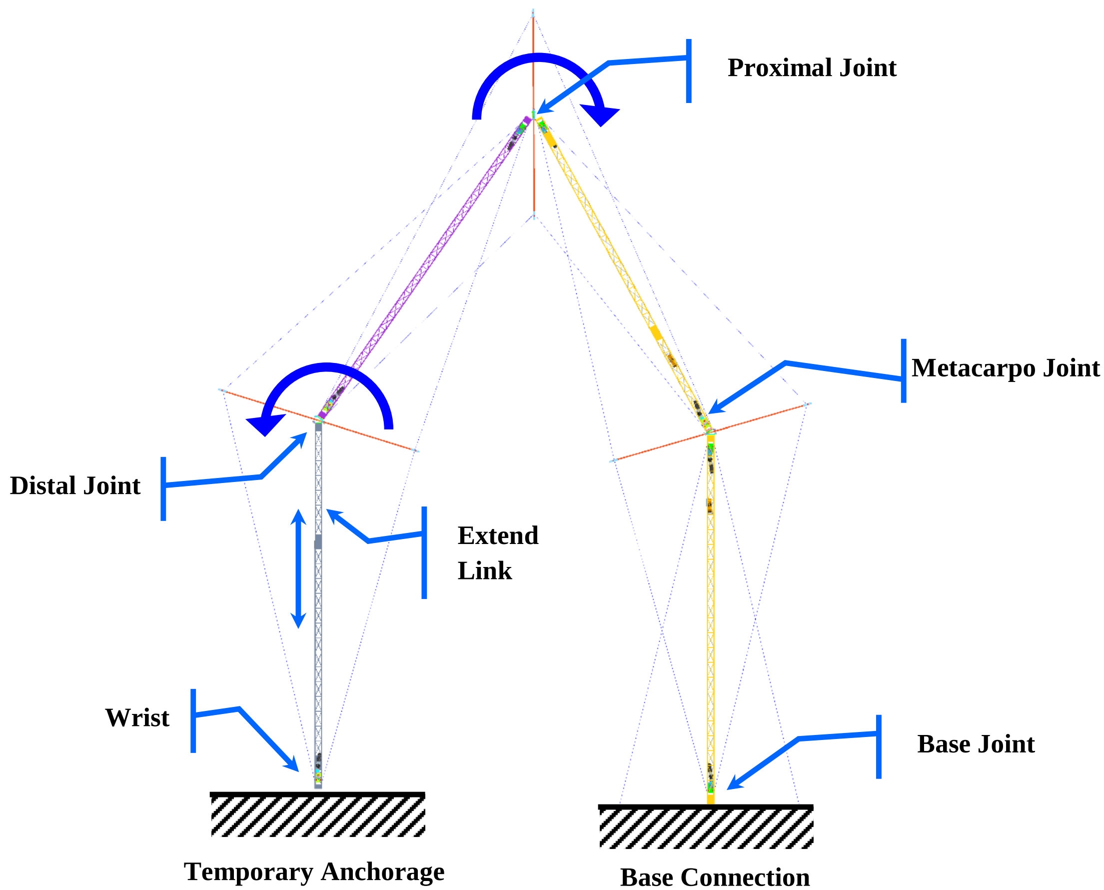


Figure 6. Method to extend TALISMAN link.

TALISMAN. Other schemes to change manipulator geometry are possible, including schemes that use additional motors or actuators to actively drive the links and spreaders to different configurations. However, there is a mass penalty associated with implementing these active approaches. Although multiple motors per joint are shown in Fig. 1, the versatility of the TALISMAN architecture makes it also possible to perform the maneuvers described here using a single motor per joint.

III. Antagonistic Capstan Drive without Springs in the Load Path for Joint Control

The second innovation disclosed here is a unique arrangement of capstans and springs that provides the ability to actively control the joint articulation, i.e., the relationship between the spreader and link, in an antagonistic arrangement without the springs being in the load path. This antagonistic arrangement of tension elements is similar to the arrangement of muscles in a human finger. A capstan works in conjunction with a running element, referred to as a cable here, which enters and exits the capstan after a few wraps. Friction between the cable and capstan prevents the cable from rotationally slipping on the capstan and enables the capstan to transfer load to the cable while drawing the cable in. Unlike a pulley, the load on the input and exit side of a capstan is different. A significant difference between a capstan and a hoist is that a hoist or winch system uses a drum, where excess cable builds up on the drum, which increases the effective drum diameter as cable is drawn in. Here, the term capstan and cable will be used, as these are familiar terms, although capstans can also be used with tapes. Springs are one means to accommodate the unequal change in length of the cables on each side of the joint during articulation as well as to maintain a small exit tension on the capstans. With this unique capstan arrangement, a continuous cable network can be used that circulates cable from one side of the link to the other, significantly reducing the total cable required to actuate a joint in the TALISMAN architecture, as shown in Figs. 7 and 8. In the figures, the motors driving the capstans and the capstan mounting hardware have been hidden for clarity. Also, the capstans are shown with different diameters to make it clear that there are two independent capstans. In practice, the capstans can have the same diameter or different diameters, depending on the results of optimizing the TALISMAN for a particular mission. The flow of a single cable is shown in Fig. 7 using the red arrows. Starting at the entry of the lower cable section as the cable enters the link, the cable passes around the larger green capstan one full revolution then proceeds from the top of the larger capstan to the cable management pulley, which is attached to the cable management spring on the right of the figure. The cable

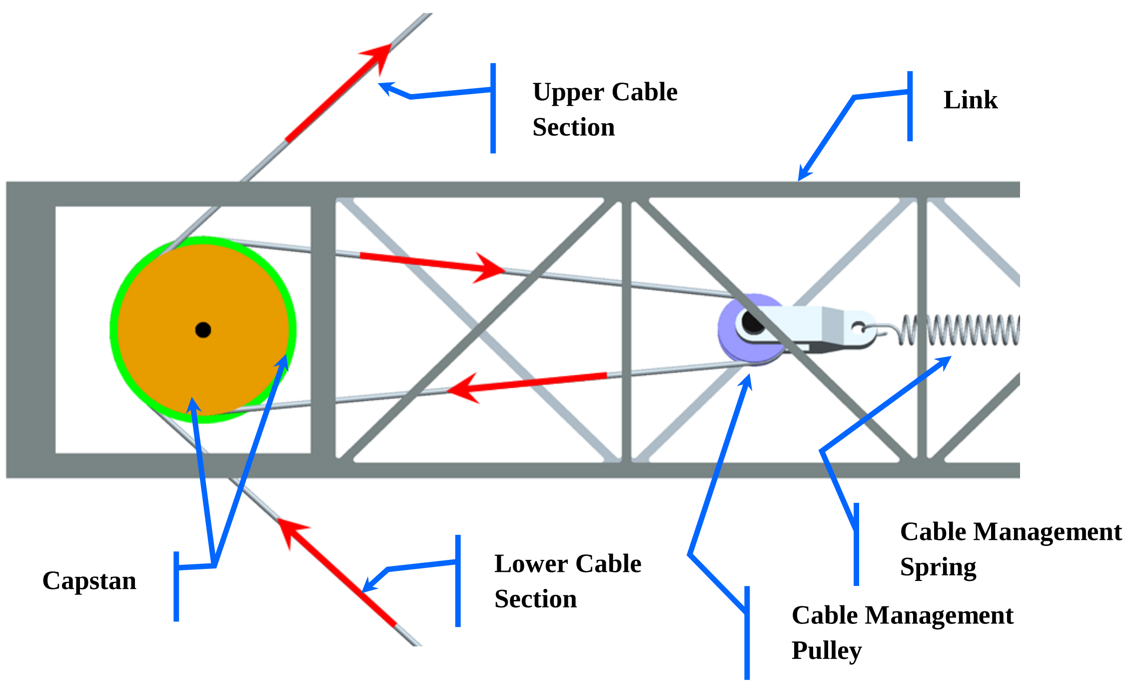


Figure 7. Antagonistic capstan arrangement side view.

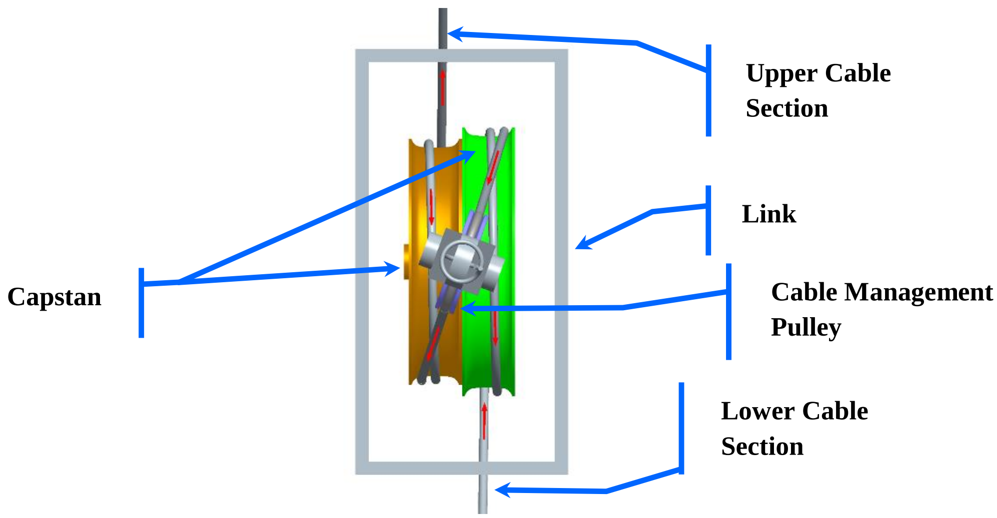


Figure 8. Antagonistic capstan arrangement, looking from joint towards capstan.

continues to the bottom of the small orange capstan and passes one full revolution around the small capstan before exiting through the top of the link (identified as the upper cable section in the figure). Capstans, unlike pulleys, enable there to be different tension forces on the cable entering and leaving the capstan. Thus, the cable management spring shown in the figures is only required to provide a small force to ensure that the cable remains in contact with the capstan. Because the force required from the spring is small, the spring can have a much smaller stiffness and thus is less massive than if it had to be included in the tension load path. Further, because the spring is not in the tension load path, the spring does not affect the fundamental frequency of the joint and the fundamental frequency of the joint can be tuned by varying the preload in the cables, with the spring arrangement managing the excess cable. A view of this arrangement looking out from the joint past the cable management pulley toward the capstans is shown in Fig. 8. By having the lower and upper cable sections enter and exit the system near the centerline of the link, this position minimizes the torque exerted on the link from the offset in these elements.

IV. Differential Capstans to Reduce Required Motor Torque

Cranes used for lifting objects use cable systems where the cable is driven by a large hoist system that takes up and wraps cable on a drum and reels the cable out to effect motion of the lifting hook. As shown in the simplified image of Fig. 9, the load from the cable must be reacted by the hoist system. This reaction torque directly affects the hoist motor and drive system as well as the brake system used to arrest hoist motion. The focus here is on reducing the reaction torque, T_H, caused by the load since this affects motor, gearbox, and brake sizing. Although present, bearing loads at the supports for the rotating elements will not be discussed. In general, the bearing loads for the differential capstan system are similar to those found in a traditional system such as depicted in Fig. 9. The motor torque acts to drive the capstan or hoist and is directly proportional to the torque required to turn a handle affixed to the hoist drum or capstan. The torque at the handle of Fig. 9 is given by

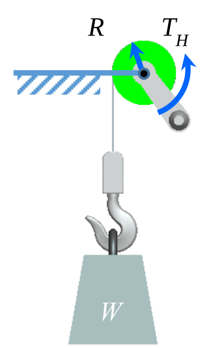


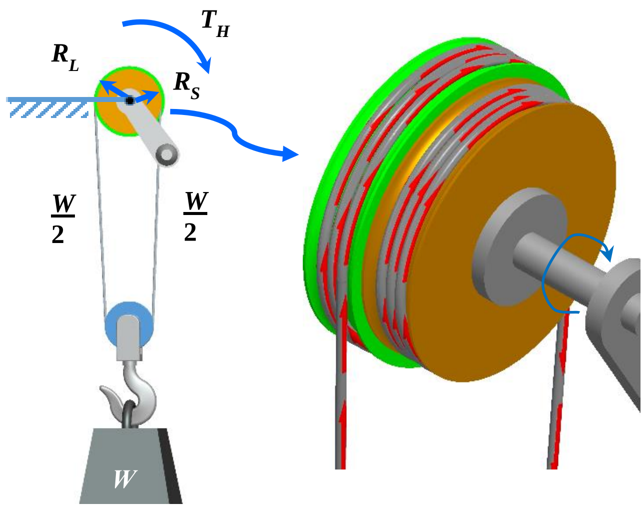
Figure 9. Simple hoist.

$$T_H = W\,R \tag{1}$$

where T_H is the handle torque, W is the lifted weight and R is the radius of the hoist drum. A significant improvement on this system is obtained using a differential windlass (also called Chinese windlass), as shown in Fig. 10. In this design, the torque applied to the handle, T_H, is proportional to the difference in the torques exerted by each line;

$$T_H = \frac{W}{2}\left(R_L - R_S\right) \tag{2}$$

where W is the weight being lifted, R_L is the radius of the larger drum, and R_s is the radius of the smaller drum. A close up of the two coupled drums is shown in Fig. 10b. As the handle is turned clockwise, cable is fed off the smaller diameter drum and taken up on the larger diameter drum. Because the larger drum has a larger circumference, more cable is taken up than released and the hook is raised. A single cable is used, and the red arrows in the figure indicate the path of the cable about the individual drums. The ratio of these drum diameters provides a gear ratio between turns of the handle and raising or lowering of the hook. The major drawback to this arrangement is that as the drum diameters become nearly equal, improving the mechanical advantage, the amount of cable that must be stored on the drums becomes large causing cable management difficulties, and an increase in mass.



a. Overview b. Close up of windlass drums

Figure 10. Differential windlass.

In contrast to this traditional approach, a novel arrangement of differential capstans to react the load created by the lifting hook is described (see Fig. 11). As with the differential windlass, the torque required to lift the load is proportional to the difference between the radii of the two capstans. This arrangement has other advantages including; 1) the ability to tune the system gear ratio by varying the ratio of capstan diameters, 2) cable enters and exits the capstan so the cable does not accumulate on the drum hence, the relationship between capstan rotational speed and cable speed does not change, and 3) wear on the cable is reduced because the cable does not over wrap on itself. Referring to Fig. 11, the part of the mechanism above the differential capstans is the cable management side of the device, including the tension spring and cable management pulley. The portion below the differential capstans is the load side of the mechanism, including the load pulley, load hook, and working load, W. A drawback to the proposed system is that the cable travels a greater distance, circulating in a loop around the cable management pulley and load pulley, making management of the extra cable as the hook is raised more challenging. As the working load is raised, the distance from the capstan axis to the load pulley, D_{WL}, decreases and the distance from the capstan axis to the cable management pulley, D_{CM}, increases (in the figure, this motion is proportional). Because of the unique architecture of the TALISMAN, the cable management issue is minimized by sharing the same cable between two tension networks.

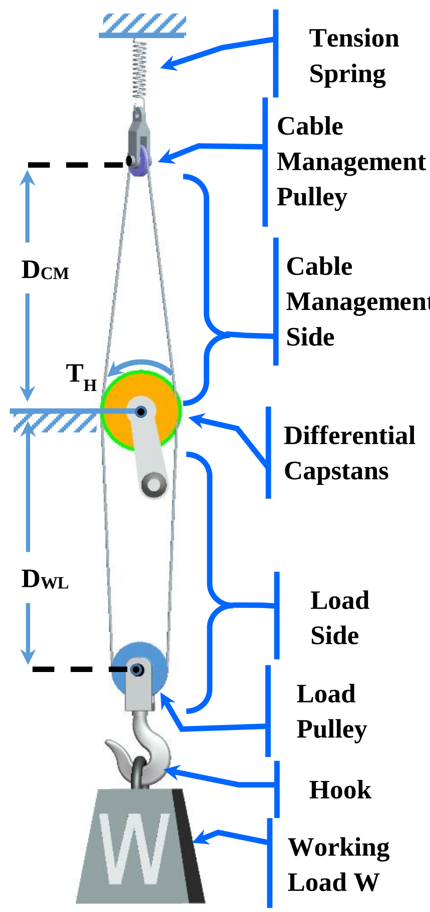
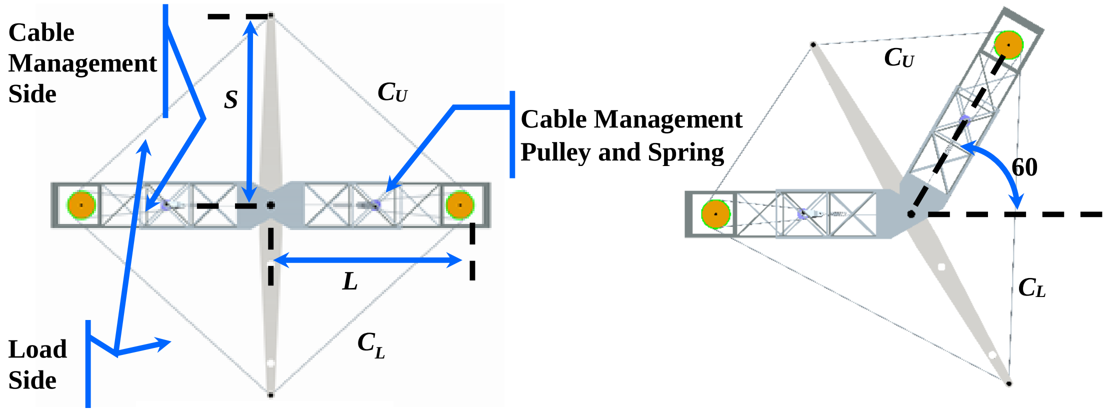


Figure 11. Differential capstan arrangement.

The use of capstans, as shown in Fig. 11, reduces the total amount of cable needed, but requires that the cable circulate. In addition, the length of cable on the cable management side, i.e., the take up side, is proportional to the length of cable on the load side. In other words, as the hook is lifted the excess cable circulates around the differential capstans and is taken up by the tension element, the spring in the figure. Thus, without additional elements such as block and tackles, the tension element travel must equal that of the load. However, the unique



a. Joint straight **b. Joint angled to 60°**

Figure 12. Sharing cable between antagonist tension elements.

TALISMAN architecture makes nearly full use of all the cable at all times by sharing the cable between a pair of antagonistic tension loops above and below the link, as will be illustrated using the joint postions shown in Fig. 12, where S is the spreader height, L is the link length, C_U is the upper cable length, C_L is the lower cable length. The load side of Fig. 11 is the portion from the spreader to the capstan identified in Fig. 12, with one tension loop above the link and one tension loop below the link. The cable management side of Fig. 11 is shared between the two tension loops and occurs inside the link as identified in Fig. 12. For simplicity, let $S = L$. With the joint in the configuration shown in Fig. 12a, the total cable length, $C_U + C_L = 2\sqrt{2}\,L = 2.82\,L$, where in Fig. 12b with the joint articulated 60°, $C_U + C_L = L + \sqrt{3}L = 2.732\,L$, a change of 3 percent of the original cable length, which is managed by the cable management pulley and spring shown in the figure.

V. Deployment System for TALISMAN

A recent focus has been on enabling the efficient transition from the packaged state to the deployed state (see Fig. 1). This deployment process uses the same motors as are used for joint articulation, which reduces the complexity and parasitic mass of the deployment system. The general deployment scheme is depicted in Fig. 13, where the joint begins in the packaged state (Fig. 13a) and unfurls to the extended state (Fig. 13c). The joint unfurls because the cables pass along the outside of the links creating an offset (Fig. 13b) about the joint axis, so that when the cables are placed in tension, a torque is generated about the joint axis causing the joint to unfurl and open to the extended position. After the joint is in the extended configuration, the spreader is released (by retracting pins) allowing the spreader to translate to the deployed position (Fig. 13d). The pins are spring loaded to extend into machined holes enabling discrete repositioning of the spreader. A photograph of the hardware used in the test is shown in Fig. 14 and is also shown undergoing a test in the facility shown in Fig. 15. The assembled spreader with the pin retraction motor mounted is shown in Fig. 14a. The pin retraction motor disengages pins to releases the spreader, which allows it to translate. A close up of the pin retraction motor and associated hardware which form a motorized turnbuckle is shown in Fig. 14b, that when activated retract a pair of pins, one on each rail, to allow the spreader to move. This system supports both deployment and dynamic reconfiguration during operation. The test facility shown in Fig. 15 includes a precision poured concrete floor that provides a 15.2 m by 21.3 m (50 ft by 70 ft) surface suitable for air-bearing operation. The blue cylinders located under the joints and at the wrist, one of which is identified in the photograph, are air bearings which float on a cushion of air. The air bearings float the manipulator to simulate zero-g operations in the plane of the floor.

The two TALISMANs shown in Fig. 15 were designed to have the same reach and in-plane stiffness as the SRMS. The resulting manipulator is 15.2 m (50 ft) long, has four links, and is shown in Fig. 1. To enable dual arm operation within the facility, the last link of the TALISMANs were removed to shorten them to approximately 11.6 m (38 ft) in length as shown in the photograph. The TALISMANs are secured to a versatile base structure enabling the distance

between the manipulator bases and the angle of the base spreader to be easily adjusted so that a variety of potential spacecraft attachment schemes can be quickly evaluated.

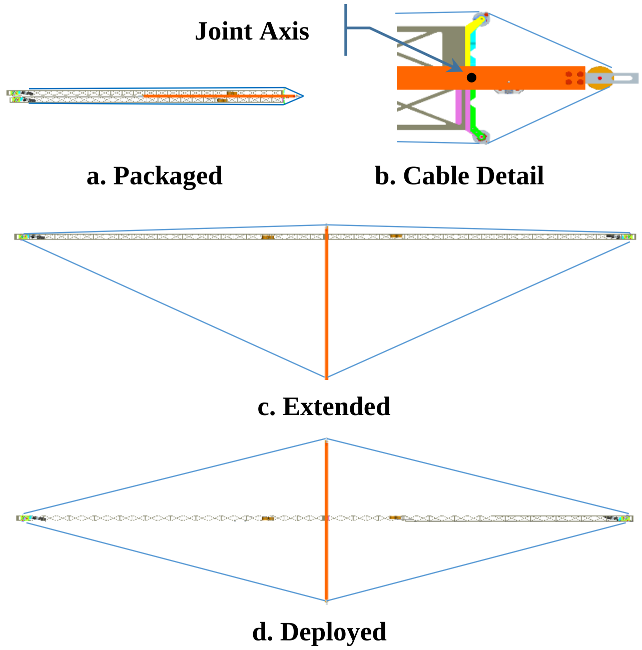


Figure 13. Single joint deployment sequence.

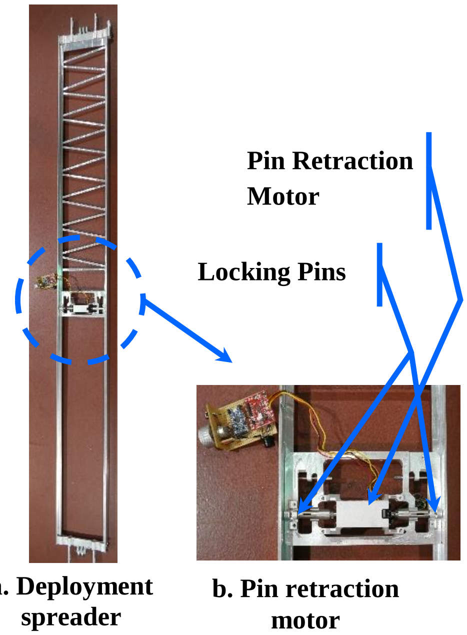


Figure 14. Deployment test hardware.

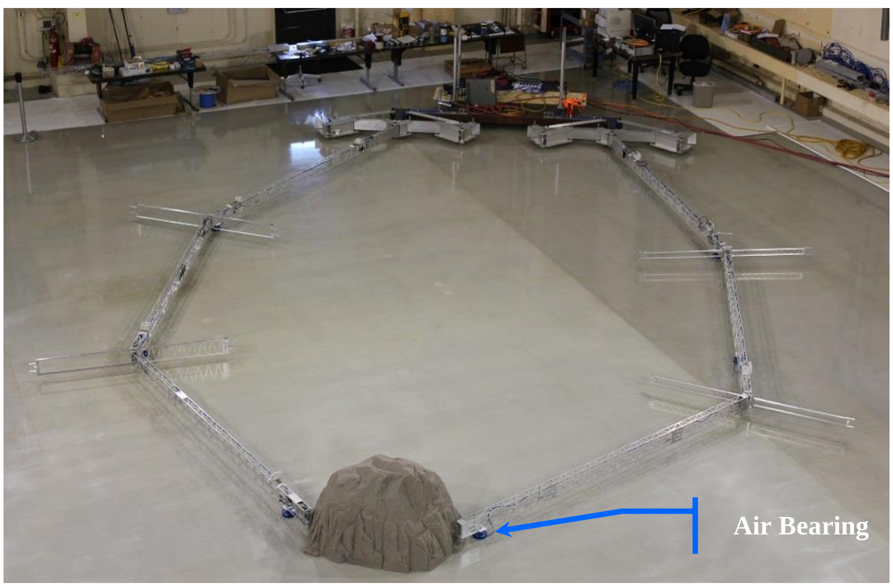


Figure 15. Multi-arm testbed in new flat floor facility.

VI. Summary and Concluding Remarks

The Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN) represents a novel new architecture for long-reach space manipulators. The antagonistic tendon actuated joint architecture allows the motors actuating the joint to be located remote from the joint axis, which simplifies the joint design, while simultaneously providing mechanical advantage for the motors and structural stiffening of the joints and links. The improved mechanical advantage for the motors, in turn, reduces the size and power requirements for the motor and gear train. This paper

described recent significant architectural improvements to the TALISMAN design that 1) improve the operational robustness of the system by enabling a manipulator to reconfigure geometrically to avoid obstacles or tune the manipulator performance for specific maneuvers, 2) enable efficient active antagonistic control of a joint while sharing cable between two antagonistic tension networks, and 3) uses a unique arrangement of differential capstans to reduce motor torque requirements by an order of magnitude.

Recently, efforts have focused on enabling autonomous deployment of a TALISMAN. The deployment mechanism design and the associated hardware system that was fabricated were described. Deployment forces are provided by the same motor systems that are used for articulation in an effort to reduce the mass and complexity associated with the deployment system. The deployment approach is undergoing tests on a TALISMAN prototype which is designed to provide the same operational performance as a shuttle-class manipulator. Two TALISMAN prototypes have been fabricated and are operational in a new facility at NASA Langley Research Center that has a large area (15.2 m by 21.3 m [50 ft by 70 ft]) air-bearing floor suitable for simulating zero-g operations.

References

[1] Doggett, W. R., Dorsey, J. T., Collins, T. J., King, B. D., and Mikulas, M. M., “A Versatile Lifting Device for Lunar Surface Payload Handling, Inspection and Regolith Transport Operations,” Proceedings of the Space Technology and Applications International Forum – 2008 (STAIF-2008), February 10–14, 2008, Albuquerque, NM.

[2] Mikulas, M. M., Yang, L. F., “Conceptual Design of a Multiple Cable Crane for Planetary Surface Operations,” NASA TM-104041, January, 1991.

[3] Patten, L., Evans, L., Oshinowo, L., Ochisor, M., Kazuharu, N., Lodewijk, A., Tabarah E., “International Space Station Robotics: A Comparative Study of ERA, JEMRMS and MSS,” 7th ESA Workshop on Advanced Space Technologies for Robotics and Automation, ASTRA 2002' ESTEC, Noordwijk, The Netherlands, November 19 - 21, 2002.

[4] Doggett, W. R., Dorsey, J. T., Jones, T. C., King, B. D., “Development of a Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN),” Proceedings of the 42nd Aerospace Mechanisms Symposium, Baltimore, MD, 2014.

[5] Dunbar, D. R., Robertson, A. R., and Kerrison, R. “Graphite/Epoxy Booms for the Space Shuttle Remote Manipulator.” *International Conference on Composite Materials*, Toronto. 1978.

[6] Kumar, P., Truss, P., and Wagner-Bartak, C. G. “System Design Features of the Space Shuttle Remote Manipulator.” *Proceedings of the Fifth World Congress on Theory of Machines and Mechanisms*. 1979.

[7] Craig, John J. *Introduction to Robotics Mechanics and Control*, 2nd Ed. Addison-Wesley Publishing Co., New York, NY, 1989.